Dynamic simulation of the soil moisture of apple under drip irrigation with dwarf rootstock in arid saline-alkali areas based on HYDRUS-1D model

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Abstract: In order to study the soil moisture dynamics and irrigation regimes during the growth period of dwarfing apples in arid and saline-alkali areas, five irrigation treatments (W1: 0.6W3, W2: 0.8W3, W3: 22.5 mm, W4: 1.2W3, W5: 1.4W3) were set up in the southern Xinjiang region. A three-year (2019-2021) field plot experiment of dwarf apple in southern Xinjiang was carried out, and the HYDRUS-1D model was used to simulate the measured data of soil moisture. The root soil moisture transport pattern, root zone soil moisture stress, apple root water absorption capacity, and water deep percolation pattern were analyzed by numerical simulation to evaluate the model's applicability to actual production in arid saline-alkali areas. Through the simulation analysis of 66 irrigation regimes, it was found that the simulated values of soil moisture content and nitrogen were in good agreement with the measured values, and the values of determination coefficient (R^2), root mean square error (*RMSE*), and consistency index (*d*) were within a reasonable range. When the sum of soil water stress and deep percolation was between 19.81-21.11 mm, the water loss of farmland reached the minimum. Considering the optimal moisture dynamic analysis in the apple root zone, the recommended irrigation system was 19 times of irrigation, an irrigation quota of 27-36 mm, and an irrigation cycle of 6 d. Through the research results and model simulation, the theoretical basis can be provided for the optimization of irrigation system for dwarf rootstock apple in arid and saline-alkali areas.

Keywords: drip irrigated apple, soil moisture dynamics, irrigation regime, numerical simulation
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1 Introduction

Water shortage is the key factor for the development of efficient water-saving irrigation technology in arid areas. Water consumption for crop growth mainly comes from rainfall and irrigation. Irrigation frequency and irrigation quota play an important role in the spatial and temporal distribution of soil water, heat, and salt, affecting the growth process of plants[1,2], and even affecting the crop yield and water use efficiency[3]. Therefore, the development of a reasonable irrigation regime has an important impact on the regulation of soil moisture and the improvement of water use efficiency in arid areas.

Field experiments are the most reliable method to explore soil moisture, heat, and salinity, but are often time-consuming and labor-intensive. At present, crop evapotranspiration and solute transport have been studied in depth. Great progress has been made in process analysis and mathematical description. There have been many simulation models for predicting water and solute transport between surface water and groundwater levels. For example, HYDRUS-1D[4], SHAW[5], SWAT[6], SALTMOD[7], etc. Compared with the field experiment, the HYDRUS-1D model is easy to operate, and the simulation verification and simulation effect of soil water, salt, fertilizer, and heat is remarkable, which can evaluate the water transport pattern and nitrogen balance in soil[8,9], as well as evaluate the correlation between root water uptake and groundwater[10].

In recent years, many researchers have used HYDRUS to

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explore the simulation of water dynamics in soil[8,11]. Some scholars have concluded that the HYDRUS-1D mode can be used to simulate and compare the changes of water flux under single factor irrigation[12]. Zhou et al.[13], based on the HYDRUS model, numerically simulated the soil water movement at different growth stages of crops, and the simulated data were significantly correlated with the measured values. The HYDRUS model can well simulate the soil water and salt dynamics in 20-40 cm soil layer[14]. However, there was a large deviation between the simulated and observed values of soil water and salt in the 0-20 cm or 40-50 cm soil layer[15]. Li et al.[16] used HYDRUS-1D to simulate the adsorption and migration of soil water, heat, and salt under drip irrigation under mulch in arid saline-alkali areas, and further optimized the irrigation system. Zheng et al.[17] constructed a water infiltration model in an arid oasis, and concluded that it could significantly increase the water absorption of plant roots. Based on the HYDRUS model, the distribution of water migration and distribution and root water absorption process under different soil textures were simulated[18]. By introducing the root water absorption module, the water migration process and water balance process under irrigation conditions are numerically calculated, and the irrigation conditions suitable for crop cultivation are derived.

Based on the HYDRUS-1D model, the organic integration of intelligent agriculture and field agriculture is realized, which provides more efficient application methods for field experiments. The combination of farmland observation and numerical simulation to study crop irrigation systems has been relatively perfect in the study of annual crops[19]. However, the research on arid zone fruit trees by HYDRUS model simulation is not deep enough, and there is a lack of analysis of soil water stress and deep water percolation in root zone. To address this problem, the purpose of this study is to construct a model of soil water transport in apple root zone based on HYDRUS-1D, to simulate and analyze the pattern of soil water stress, root water uptake, and deep water percolation in root zone, and to explore and evaluate the applicability of the model in actual production in arid areas. It is helpful for simulating the water fluxes under different irrigation regimes in arid zones, and for providing theoretical support for rational optimization of irrigation systems.

2 Materials and methods

2.1 Field experiment

2.1.1 Experimental site

The experiment was conducted in 2019-2021 in Alar City, Xinjiang Production and Construction Corps. The orchard (40°39′N, 81°16′W, average altitude 1013 m) is 15 km away from the urban area of Alar City, with a warm temperate arid desert climate. The annual average temperature is (11±1)°C, the annual rainfall is about 50 mm, the evaporation is as high as about 2100 mm, the annual total solar radiation is 552.73 kJ/cm^2, the annual sunshine duration is 2900 h, and the frost-free period is 203 d. The soil texture is sandy loam. The field water holding capacity of 0-120 cm soil is 18.5% (volumetric water content), the soil bulk density is 1.51 g/cm^3, and the groundwater level is around 3.0 m. The soil fertility is listed in Table 1.

Table 1 Soil nutrient content in test area

Organic matter/ (g·kg^{-1})	Available phosphorus/ (mg·kg^{-1})	Effective boron/ (mg·kg^{-1})	Rapidly available potassium/ (mg·kg^{-1})	Alkaline hydrolysis nitrogen/ (mg·kg^{-1})	Total nitrogen/ (mg·kg^{-1})	Ammonium nitrogen/ (mg·kg^{-1})	Nitrate nitrogen/ (mg·kg^{-1})
11.05	3.2	0.6	33	10	176	2.01	1

2.1.2 Experimental design

The experiment was carried out from April to August 2019-2021 with mature ‘Royal Gala’ apples as the research subjects. Considering the single factor irrigation, five irrigation regimes were set, which were 13.5 mm (W1), 18 mm (W2), 22.5 mm (W3), 27 mm (W4), and 31.5 mm (W5), respectively. Irrigation was carried out when the reference crop evapotranspiration (ET_o) - rainfall (P) was accumulated to 22.5 ± 3 mm. Figure 1 is the ET_o from 2019 to 2021, calculated using the Penman-Monteith Equation (1) modified and recommended by FAO-56[20]:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{900u_2}{T+273}(e_a - e_d)}{\Delta + \gamma(1+0.34u_2)} \tag{1}$$

where, ET_o is the reference crop evapotranspiration, mm; R_n is the net radiation, MJ/m^2·d; G is soil heat flux, MJ/m^2·d; γ is the hygrometer constant, kPa/°C; T is the average air temperature, °C; u_2 is the wind speed at a height of 2 m above the ground, m/s; e_a is the air saturated water pressure, kPa; e_d is the actual air water pressure, kPa; Δ is the tangent slope at T on the temperature-saturated water vapor pressure relationship curve, kPa/°C.

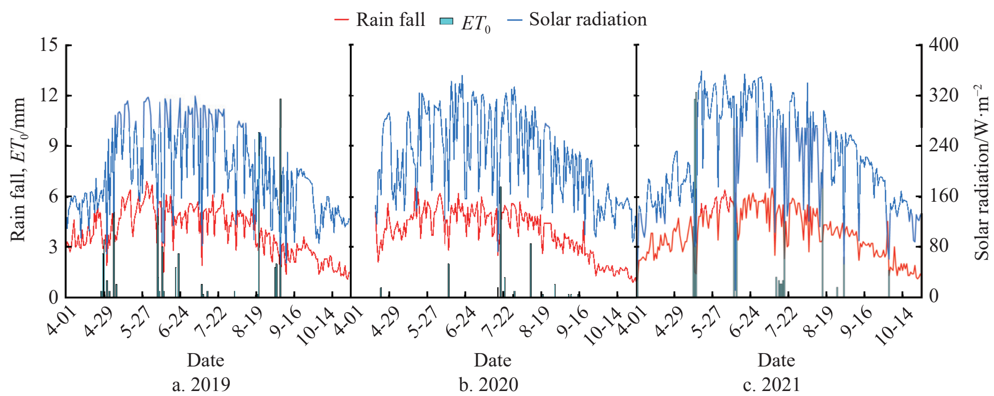


Figure 1 ET_o and rainfall data in the growth period from 2019 to 2021

The apples were planted with dwarf rootstock, and the row spacing was 3.5 m×1 m. The drip irrigation method was one row and one pipe, with a dripper flow rate of 4 L/h, and a drip hole spacing of 30 cm. Fertilization, plant protection, and other field measures were consistent with local orchard management recommendations.

2.1.3 Measurements

The HOBO U30 automatic moisture monitoring instrument (Onset, USA) was installed under the drip irrigation pipe in each plot to monitor the soil moisture dynamics. The soil moisture sensor measures the soil volumetric water content, and the buried depth was 20, 40, 60, 80, 100, and 120 cm. Each burial depth was repeated three times. The soil moisture content was measured by drying method in each growth stage for calibration.

Meteorological parameters were measured by HOBO U30 automatic weather station (Onset, USA), and recorded once every 30 min. The measurement indices included temperature, relative humidity, solar radiation, wind speed, and rainfall.

2.2 Model description

This article does not contain any research involving humans or animals.

2.2.1 Soil water transport model

The HYDRUS model was used for numerical simulation, and the modules of water flow, root water uptake, and root growth were selected. The water flow section was constructed according to the principle of soil water transport, which was based on the soil moisture content as the independent variable. The root water uptake condition is expressed by the Darcy-Richards equation as Equation (2)[21]:

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial z}\left[D(h)\frac{\partial(\theta)}{\partial z}\right]-\frac{\partial K(\theta)}{\partial z}-s \tag{2}$$

where, θ is the volumetric soil water content, cm^3/cm^3; t is time, d; z is soil depth, cm; K is the soil hydraulic conductivity, cm/d; h is the hydraulic head pressure, cm; and S is the crop root water uptake, cm^3/cm^3·d.

The parameters in the VG model are determined by soil water dynamics in Equations (3) and (4)[22,23]:

$$\theta(h)=\begin{cases}\theta_r+\dfrac{\theta_r+\theta_s}{(1+|\alpha h|^n)^m}, & (h<0)\\ \theta_s, & (h\geq 0)\end{cases} \tag{3}$$

$$K(h)=K_s\frac{\left[1-|\alpha h|^{n-1}(1+|\alpha h|^n)^{-m}\right]^2}{(1+|\alpha h|^n)^{m/2}} \tag{4}$$

where, θ_s and θ_r are the soil saturated and residual water content (cm^3/cm^3), respectively; K_s is the soil saturated hydraulic conductivity, cm/d; α, n, and m are empirical coefficients, and m=1–1/n (n>1).

2.2.2 Evaporation and transpiration

The potential evapotranspiration (ET_c) of the apple field is calculated as the following Equations[24]:

$$ET_c=K_cET_o \tag{5}$$

$$T_p=ET_c(1-e^{-KLAI}) \tag{6}$$

where, ET_c is the potential water requirement for the crop, mm; K_c is the actual crop coefficient, kPa; T_p is the potential transpiration, mm; and LAI is the leaf area index.

2.2.3 Precision validation

Optimization function of irrigation regime and its expression is as described in Equation (7):

$$f=\min\left(DP_{ij}+\left|WS_{ij}\right|\right) \tag{7}$$

where, DP is the deep percolation, mm; WS is the amount of water stress, mm; i is the irrigation quota, mm; j is the irrigation frequency, d; and f is the optimization function, of which the smaller the value, the better the function simulation effect.

Calculation of water stress is described in Equation (8):

$$WS_{ij}=\begin{cases}10\sum_{n=1}^{6}H(60\%\theta_{lf}-\theta_{lj}), & \theta_{lj}<\theta_{lf}\\ 0, & \theta_{lj}\geq\theta_{lf}\end{cases} \tag{8}$$

where, H is the soil depth, cm; θ_{lf} is the field water holding capacity, cm^3/cm^3; θ_{lj} is the soil water content (cm^3/cm^3) of l layer j day.

The upper boundary is the atmospheric boundary, the lower boundary is free drainage, and the left and right boundaries are zero flux. According to the soil texture and mechanical composition of the test site, the hydraulic characteristic parameters of each soil layer (soil residual water content, soil saturated water content, saturated hydraulic conductivity, and the model parameters α and n) were predicted by an artificial neural network using the Rosetta software of HYDRUS software. The meteorological data were obtained by a HOBO instrument, including temperature, humidity, rainfall, and radiation, and the potential evapotranspiration was calculated by the Penman Monteith Equation. The simulation time span was 2019-2021, in which the 2021 data were used as the model calibration data, and the 2019-2020 data were used as the model verification data. The optimized parameters are listed in Table 2.

Table 2 Soil parameter inversion

Soil horizon/ cm	Cosmid/ %	Powder particle/%	Grit/ %	θr/ cm^3·cm^{-3}	θs/ cm^3·cm^{-3}	A/ cm^{-1}	n	Ks/ cm·d^{-1}
0-20	0.77	4.24	94.99	0.0500	0.4579	0.0441	3.8425	600.00
20-40	1.08	6.33	92.59	0.0488	0.4390	0.0411	2.2098	500.00
40-60	0.67	3.15	96.18	0.0488	0.4390	0.0411	2.2098	500.00
60-80	0.73	3.73	95.54	0.0497	0.4088	0.0161	2.2200	189.62
80-100	1.28	8.42	90.30	0.0440	0.3841	0.0259	1.6805	187.37
100-120	1.41	11.75	86.84	0.0434	0.3816	0.0459	1.5312	69.58

2.2.4 Statistical analysis

The determination coefficient (R^2), root mean square error ($RMSE$), standard root mean square error ($NRMSE$), and consistency index (d) were used to evaluate the simulation accuracy, calculated as follows[25,26]:

$$RMSE=\sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i-Q_i)^2} \tag{9}$$

$$NRMSE=\sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i-Q_i)^2}\times 100\%/\bar{O} \tag{10}$$

$$R^2=\left(\frac{\sum_{i=1}^{n}\left(S_i-\bar{S}\right)\left(O_i-\bar{O}\right)}{\sqrt{\sum_{i=1}^{n}\left(S_i-\bar{S}\right)^2\sum_{i=1}^{n}\left(O_i-\bar{O}\right)^2}}\right)^2 \tag{11}$$

$$d=1-\frac{\sum_{i=1}^{n}\left(S_i-\bar{Q}_i\right)^2}{\sum_{i=1}^{n}\left(\left|S_i-\bar{O}\right|+\left|O_i-\bar{O}\right|\right)^2} \tag{12}$$

where, O_i and S_i are observed and simulated values, respectively; n is the number of measured values; $\bar{O}$ and $\bar{S}$ are the averages of the observed and simulated values, respectively.

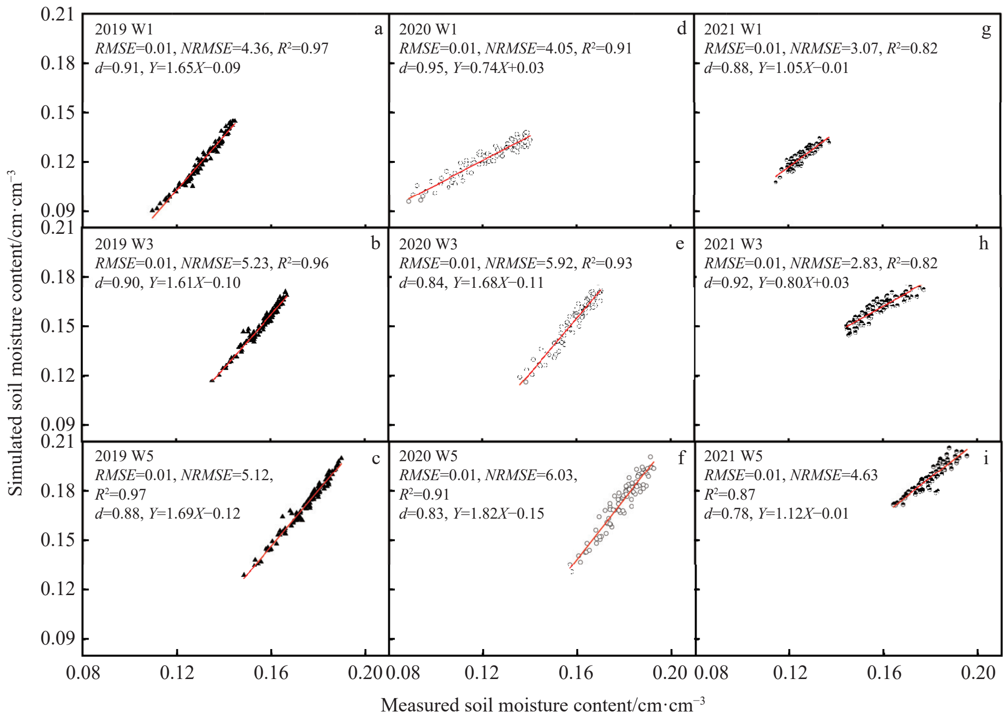
3 Results and discussion

3.1 Parameter calibration of HYDRUS model

In this study, the measured data of soil moisture, water consumption, deep percolation, and rainfall during the whole apple growth period in 2021 were used to correct the parameters of HYDRUS-1D model. The corrected model parameters and 2019-2020 measured data were used to verify the accuracy of the model parameters. The trial-and-error method was used to optimize the hydraulic characteristic parameters in the HYDRUS model. α, n, and Ks are the main optimization objectives of the model to make the model satisfy the convergence condition, which ultimately ensures that the reliability of the simulation is a necessary prerequisite for the application of the model. As shown in Figure 2, the simulated value of soil moisture in the calibration period is higher than the measured value, while the measured value in the verification period is slightly higher than the simulated value, indicating that the simulated value is in good agreement with the measured value. The values of R^2, *RMSE*, *NRMSE*, and d for the calibration period were 0.96, 0.01, 4.90, and 0.89, respectively, while the values of R^2, RMSE, NRMSE, and d for the validation period were 0.87, 0.01, 4.42, and 0.86, respectively, indicating that the model was well calibrated, but the evaluation accuracy in the validation period was slightly lower than the accuracy in the calibration period.

3.2 Verification and evaluation of HYDRUS model

Figure 3 shows a comparative evaluation of the measured values of soil moisture at all observation points in the 0-120 cm soil layer and the simulated values of the HYDRUS-2D model. The results showed that the surface soil moisture (0-40 cm) was easily disturbed by irrigation, precipitation, and soil evaporation[27], while deep soil moisture tended to be stable. The overall accuracy of the validated HYDRUS-1D model for simulating soil water movement in the three-year phenological period is within an acceptable range, and the deviation between the simulated value and the measured value is small.

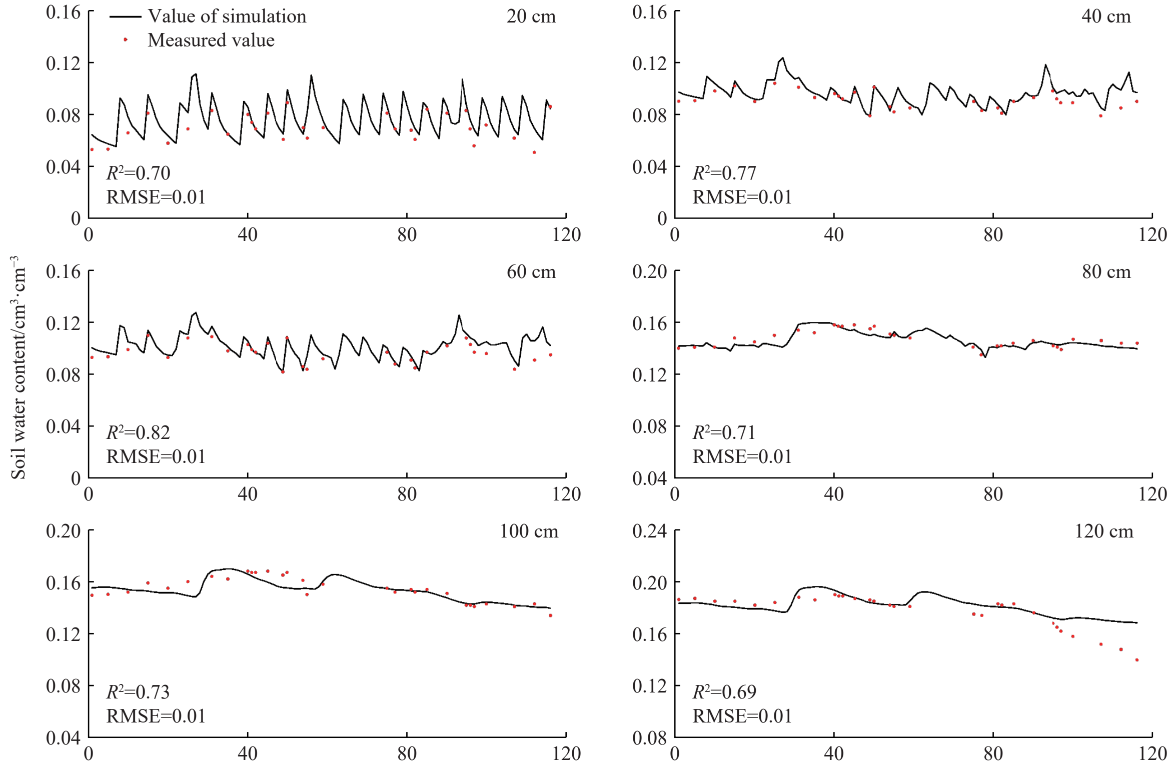


Note: a, d, g are the simulation and verification results of soil water content model in 13.5 mm irrigation treatment from 2019 to 2021; b, e, h are the simulation and verification results of soil water content model of 22.5 mm irrigation treatment from 2019 to 2021; c, f, i are the simulation and verification results of soil water content model in 31.5 mm irrigation treatment from 2019 to 2021.

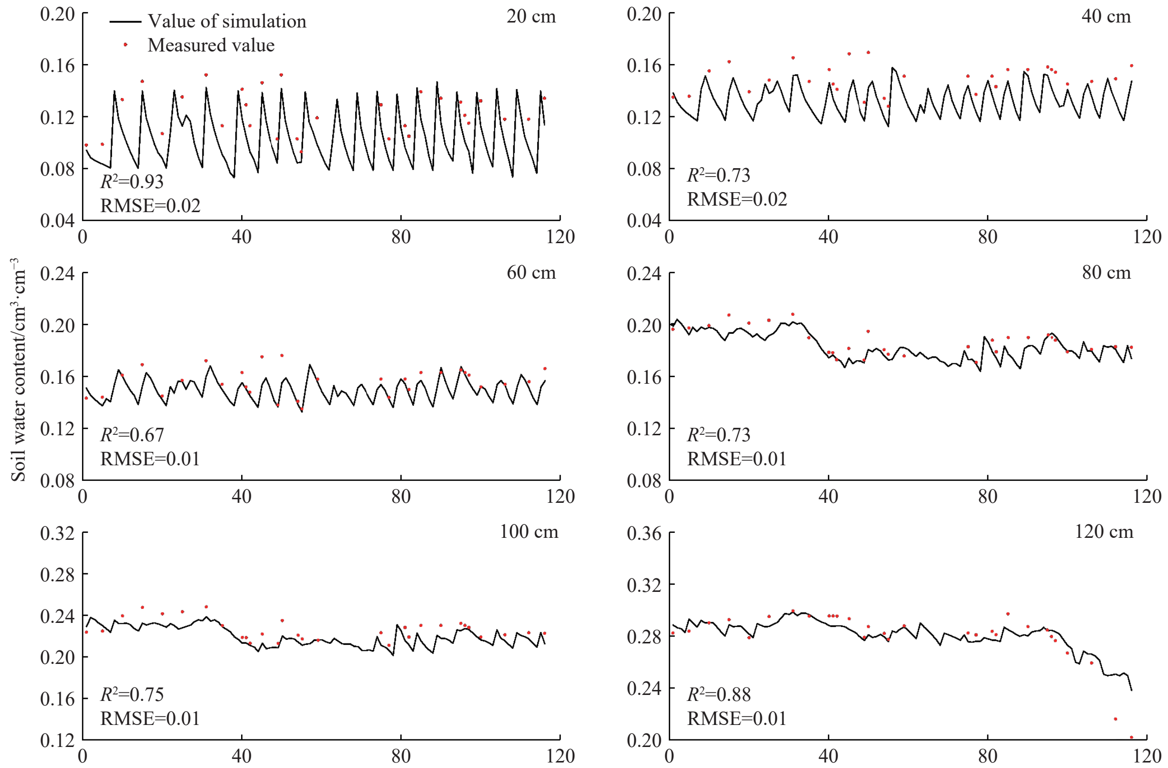
Figure 2 Simulation and verification diagrams of model parameters

The soil moisture difference of the calibration parameters estimated by HYDRUS-1D for the three-year phenological period simulation is small, which is close to the measured value (Figure 3). Under the condition of low irrigation amount, the accuracy *RMSE* of the evaluation index of the three-year phenological period ranged from 0.01 to 0.02 cm/cm and from 0.74 to 0.84 for R^2, indicating good verification results. However, the evaluation indices of 0-40 cm and 100-120 cm soil layers were poor, which may be due to the small irrigation amount in this treatment. Surface soil moisture is easily disturbed by environmental factors and fluctuates greatly. The amount of irrigation water that can reach the deep soil is less, and the difference in soil moisture change is not obvious.

In the medium irrigation treatment, the simulation accuracy RMSE for the calibration period was 0.02 cm/cm, and R^2 was 0.78. The simulation accuracy RMSE for the validation period ranged from 0.01 to 0.03 cm·cm^{-1}, and R^2 from 0.80 to 0.88, and the results of the calibration period and the validation period were in good agreement. In high water treatment, the evaluation results in 2019 were *RMSE*=0.01 cm/cm, R^2=0.92; in 2020, *RMSE*=0.02 cm/cm, R^2=0.81; and in 2021, *RMSE*=0.02 cm/cm, R^2=0.78. It can be seen that the evaluation accuracy and simulation degree are high, indicating that the simulated values are close to the observed values and can reflect the actual environmental conditions. Among them, the simulation accuracy of shallow soil (0-40 cm) was R^2=0.83, the simulation accuracy of the middle soil layer (40-80 cm) was R^2=0.78, and the simulation accuracy of the deep soil layer (80-120 cm) was R^2=0.86. This indicates that the deep soil moisture is



a. Comparison of simulated value and actual value of 13.5 mm irrigation treatment in 2021



b. Comparison between the simulated value and the actual value of 31.5 mm irrigation treatment in 2021

Figure 3 Measured and simulated values of volumetric soil water content

more stable, resulting in a better simulation effect of the model on deep soil moisture, while the model has a poor simulation effect on middle soil moisture, which may be due to the heterogeneity of the middle soil layer.

In each irrigation treatment, the simulated values of some soil layers were significantly higher than the measured values at the end of the irrigation stage, which may be attributed to the fact that the soil was taken after the last irrigation in the growth period, and there was no water supplement, resulting in a significant decrease in soil moisture during this period, while the simulated values did not clearly show the actual situation.

At the end of the growth period of cotton, the simulated value of soil water content in some soil layers of each irrigation treatment was significantly higher than the measured value. The reason may be that this stage has entered the boll opening period, and there is no water supplement of irrigation water, resulting in a significant decrease in soil moisture during this period, and the simulation value does not clearly reflect the actual situation.

3.3 Optimization of irrigation regimes

Soil evaporation, transpiration, and deep percolation are included in the water consumption of farmland[28]. The important conditions for deep percolation are irrigation and rainfall. Based on the field data, the HYDRUS model was used to simulate the deep percolation of soil at the daily scale. As can be seen from Figure 4, the deep percolation in the experimental area from 2019 to 2021 was 10.61-378.88 mm, with an average of 184.06 mm, accounting for 4.18%-58.92% of the total infiltration of surface soil and 3.47%-246.02% of the total rainfall. The peak value of deep percolation appeared in the fruit enlargement period, with values ranging from 9.19 to 261.50 mm, accounting for 25.01% and 17.21%, respectively, of the deep percolation in other growth periods.

At the same time, deep soil moisture and infiltration were closely related, and deep infiltration was positively correlated with irrigation amount. The apple water recharge in the experimental site originated from irrigation, and the irrigation quota had a great influence on the changes of apple water consumption and deep infiltration. The water consumption within each growing season, in descending order, was as follows: flowering and fruit setting stage (22.86-72.60 mm), fruit maturity stage (51.57-131.45 mm), and fruit expansion stage (218.71-542.89 mm). The average water stress in the growing season of each year was 255.55-6841.91 mm, and the deep percolation was 174.85-201.75 mm, accounting for 38.20%-38.51% of the water consumption in the whole growth period (Figure 5).

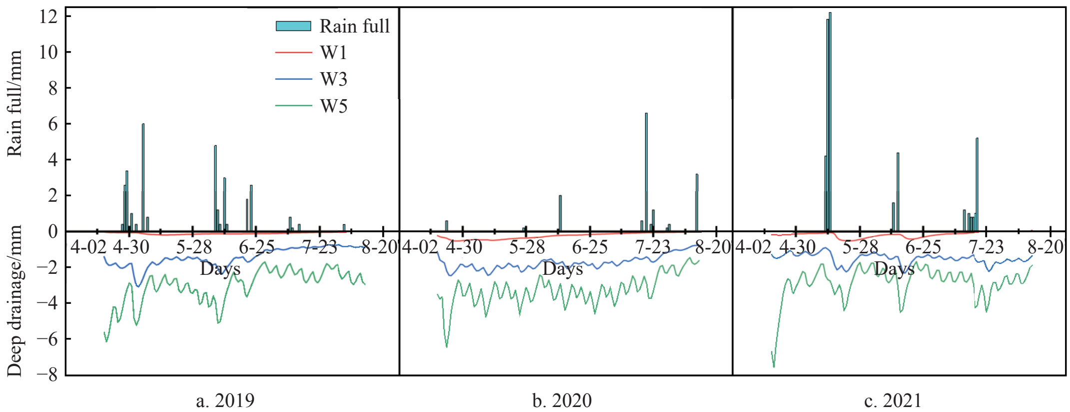


Figure 4 Rainfall and deep percolation from 2019 to 2021

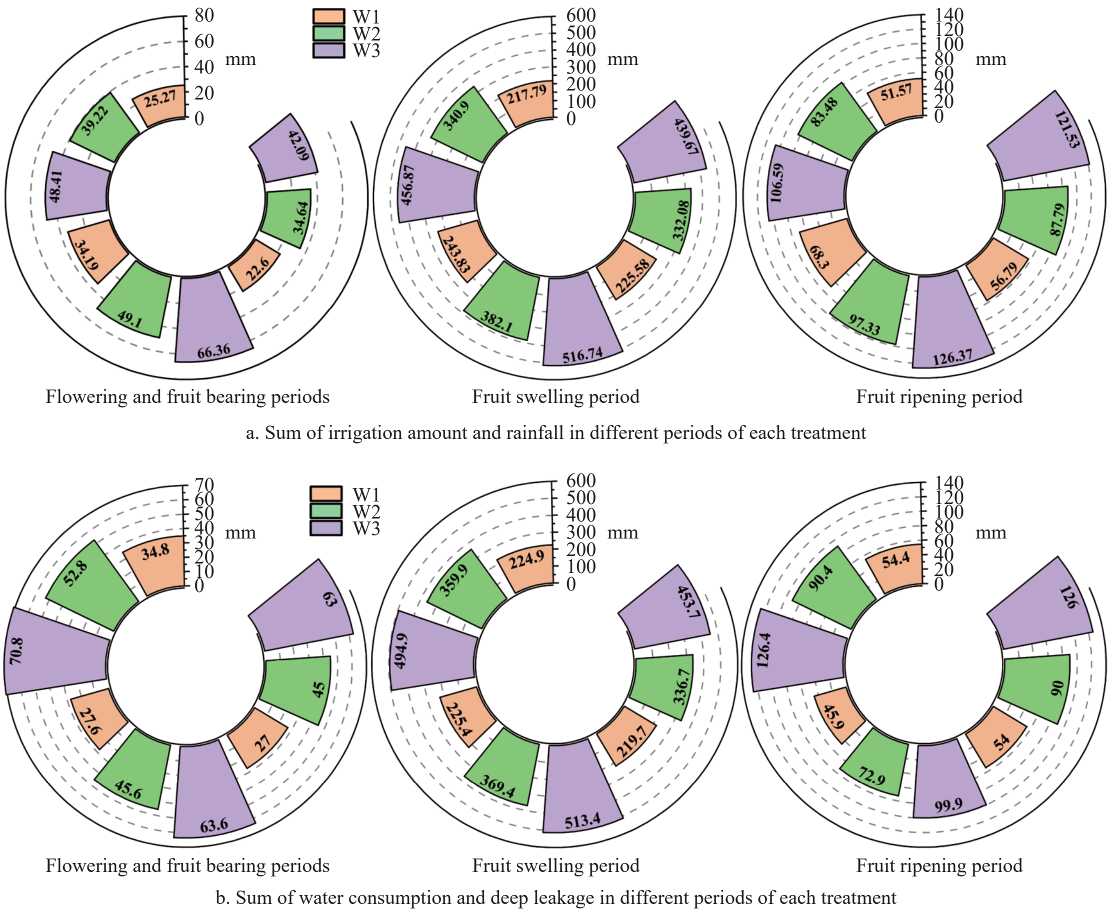


Figure 5 Source of water in each growth stage

The water stress of irrigation guided by meteorology was greater than that of irrigation guided by field. Finally, through calculation, it was found that the simulated irrigation quota was greater than the irrigation quota obtained from comprehensive agronomic characteristics[29]. This occurred because the HYDRUS model was constructed to optimize the irrigation regime based on factors such as soil moisture, soil properties, and crop growth, but did not take into account the apple yield factor, which led to deviations in guiding irrigation in actual production[30].

3.4 Scenario simulation

Root water absorption capacity is one of the key factors affecting the simulation of soil water movement, and it is an important process in SPAC cycle[9,31]. In this study, it was found that the water absorption capacity of roots increased first and then decreased with the increase of irrigation interval, which was similar to the research results of Surendran[32]. Increasing the irrigation interval would affect the water absorption capacity of roots. When the irrigation tension threshold was exceeded, it would lead to a decrease in stomatal conductance and osmotic pressure, thus limiting the water holding capacity of plants. The estimation of deep percolation is of great significance to the analysis of water balance analysis of groundwater recharge. For example, changes in meteorological conditions such as precipitation or potential evapotranspiration can cause changes in deep percolation[33]. The field measured data were used to construct a soil water transport model based on HYDRUS-1D to explore the optimal solution of the set of irrigation regime options by setting up different irrigation regime scenarios. In this study, firstly, six irrigation regimes and 11 irrigation intervals were used to simulate 66 scenarios of apple irrigation regimes (Table 3). Secondly, the simulation year was selected by rainfall. The rainfall in 2021 was 30.6 mm, and the rainfall in 2022 was 23.0 mm. Therefore, the meteorological data in 2021 were selected to simulate the apple irrigation regime (Figure 6). After optimizing the model, the recommended drip irrigation regimes for drip-irrigated apples in southern Xinjiang were: irrigation quota of 27-36 mm, irrigation frequency of 19 times, and irrigation quota range of 513.0-684.0 mm[34] (Figure 7).

Table 3 Model situation setting

Irrigation norm/mm	Irrigation frequency/times										
	2	3	4	5	6	7	8	9	10	11	12
13.5	A1B1	A1B2	A1B3	A1B4	A1B5	A1B6	A1B7	A1B7	A1B8	A1B9	A1B10
18.0	A2B1	A2B2	A2B3	A2B4	A2B5	A2B6	A2B7	A2B7	A2B8	A2B9	A2B10
22.5	A3B1	A3B2	A3B3	A3B4	A3B5	A3B6	A3B7	A3B7	A3B8	A3B9	A3B10
27.0	A4B1	A4B2	A4B3	A4B4	A4B5	A4B6	A4B7	A4B7	A4B8	A4B9	A4B10
31.5	A5B1	A5B2	A5B3	A5B4	A5B5	A5B6	A5B7	A5B7	A5B8	A5B9	A5B10
36.0	A6B1	A6B2	A6B3	A6B4	A6B5	A6B6	A6B7	A6B7	A6B8	A6B9	A6B10

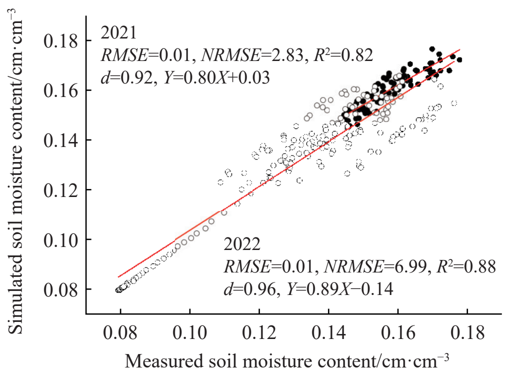
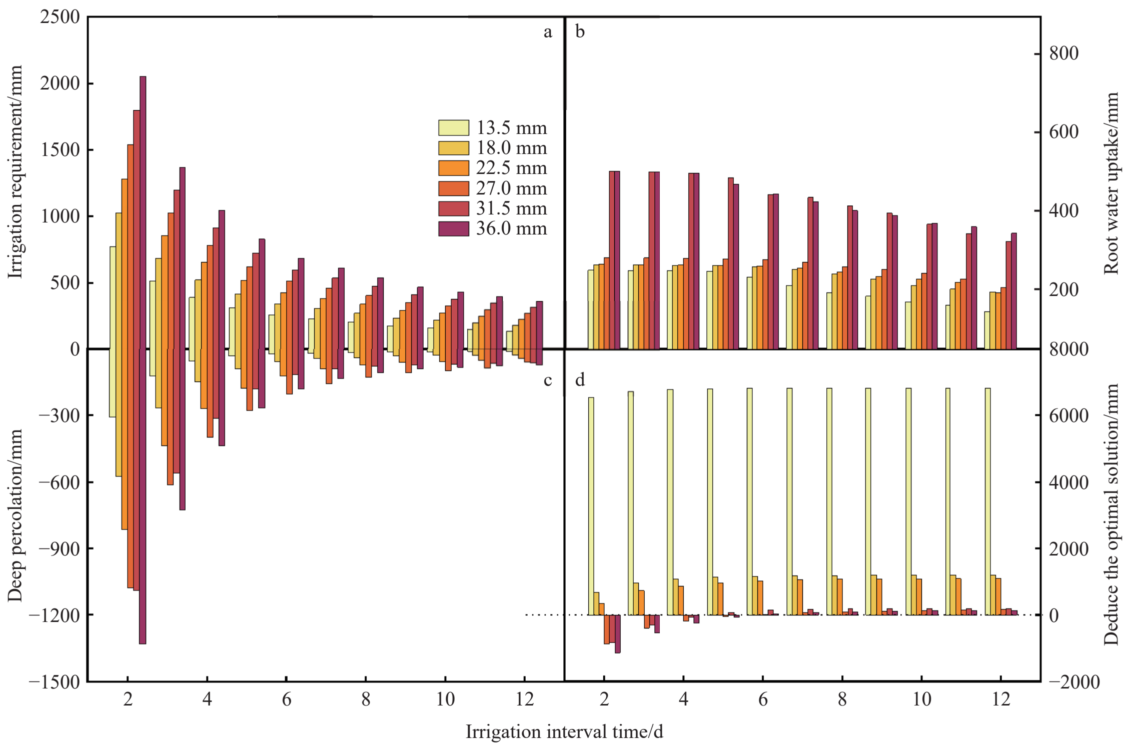


Figure 6 Simulation and validation for 2021-2022



Note: a, b, c are the variation values of irrigation quota, root water absorption, and deep seepage under different simulation scenarios; d is the optimal solution.

Figure 7 Irrigation quota, root water uptake, and deep percolation under different scenarios

The results showed that during the whole phenological period, the deep percolation reached a maximum value of 121.23 mm. The deep percolation at the flowering and fruit setting stage and the fruit maturity stage accounted for 27.70% and 23.55% of the total growth period, respectively. Similar to the previous research results, the specificity of crops in different growth stages was significant.

Although transpiration and percolation originated from the same water source during the growth period, there were differences in the rates of their flux[35]. The deep soil moisture was closely related to the infiltration, while the deep infiltration was positively correlated with the irrigation amount. Similar to the results of previous research, this indicates that the water dynamics below root zone are mainly dominated by active water storage, while the water dynamics around the root zone are dominated by passive water storage, and the deep infiltration increases with the increase of irrigation amount[36,37]. The simulation results of 66 apple irrigation regimes showed that when the sum of water stress and deep percolation was 19.81-21.11 mm, the water loss of farmland decreased to a minimum. After optimizing the model, the recommended irrigation regime for drip irrigation of apples in arid areas was an irrigation quota of 27-36 mm, 19 irrigation times, and an irrigation period of 6 d.

4 Conclusions

In this study, the HYDRUS-1D model was calibrated on the basis of a three-year experiment to analyze the dynamic of soil moisture in arid zones. The effects of root water uptake and deep percolation on irrigation regime were considered in the scenario simulation. The main conclusions are as follows:

(1) The simulation results of calibrated HYDRUS-1D soil moisture content under the consideration of water consumption, deep percolation, and rainfall did not differ much. The simulation results were in good agreement with the observed data, which could better reflect the differences in the migration of soil moisture of apple in the arid zone. The maximum value of RMSE was 0.02 cm/cm, and the minimum values of R^2 and d were 0.88 and 0.96, respectively.

(2) The results of scenario simulation showed that when the sum of soil water stress (60% of field capacity) and deep percolation was 19.81-21.11 mm, the amount of water loss from the farmland was reduced to a minimum. After optimizing the model, the recommended irrigation regime for apple planting with dwarf rootstock in arid areas was 19 times of irrigation, an irrigation quota of 27-36 mm, and an irrigation period of 6 d.

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